Navigation Challenges for the Orbit Phase of NEAR Shoemaker

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When the Near Earth Asteroid Rendezvous - Shoemaker (NEAR) spacecraft began its orbit about the asteroid 433 Eros on February 14, 2000, it marked the beginning of many firsts for deep space exploration. NEAR was the first spacecraft from any country to orbit an asteroid. As a result, the design and estimation techniques necessary to plan and execute its orbit about an irregularly shaped small body had to be developed and tested as the mission progressed. Knowledge of the mass, gravity distribution, and spin state of Eros had to be quickly improved on final approach in order to predict the effect of trajectory correction maneuvers for capture and orbit control around Eros. The navigation challenge for the orbit phase was to adapt the orbit plan while adjusting for the crudely known asteroid physical parameters. Improvements in the estimates of Eros' physical parameters as the spacecraft approached and inserted into orbit about the asteroid, were crucial to mission success. Unlike a planetary orbiter, the very low gravity of Eros ($\mu = 4.46 \times 10^{-4}$ km^3/s^2) meant that the spacecraft could easily escape or crash into the surface of Eros with small changes in velocity. This placed additional demand on navigation accuracy while also imposing a generally shorter response time than that usual for planetary orbit missions.

The NEAR mission was managed and the spacecraft was built by the Johns Hopkins University, Applied Physics Laboratory in Laurel, Maryland. Since the initial mission concept in 1992, the design and implementation of the NEAR navigation system have been the responsibility of the Jet Propulsion Laboratory, California Institute of Technology. This paper will show the unique features of navigation and mission design related to orbiting an asteroid and to designing a robust navigation system for the NEAR spacecraft. The problem of navigating a spacecraft about an asteroid is made difficult by the relative uncertainty in the asteroid physical properties that perturb the orbit. To help solve this problem, the navigation system for NEAR used NASA's Deep Space Network radio metric Doppler and range tracking, along with the new navigation technologies of optical landmark tracking and laser ranging to the asteroid surface. The performance of each of these data types in the navigation solutions will be presented. This paper will not cover the low altitude flyovers or landing of NEAR, as those topics are discussed in a companion paper submitted to this conference.

One example of the impact of imprecise knowledge about Eros before arrival was the uncertainty in the orientation of its rotation pole. The pre-arrival estimates of the orientation for the rotation pole of Eros varied by more than 4 degrees. After obtaining the initial landmark tracking during the early orbit phase, the navigation team was able to estimate the pole orientation to within 0.05 degrees, one sigma. This was important not only to orient the gravity field model for subsequent orbit determination and prediction, but it also impacted the mission design by placing a more precise date at which Sun would cross Eros' equator. As a result of this update, a maneuver originally designed to place the spacecraft into a polar orbit in July 2000, was moved by more than a week.

Similarly, the plan for orbit size and orientation during the year long science gathering phase was updated a total of seven times during the orbit in response to increased knowledge of the physical parameters and to improved navigation performance as the data taking and processing methods were refined. Because of spacecraft pointing constraints and the requirement to keep the solar arrays illuminated, the orbits were designed to lie within 30 degrees of the "Sun plane-of-sky" (SPOS), the plane normal to the Sun-Eros line. The orbit phase lasted from the insertion burn on February 14, 2000 to the landing on February 12, 2001. Figure 1 shows the different orbit radii for the entire orbit phase projected into the SPOS. The orbit radius and inclination relative to the Eros equator were varied during this phase to accommodate various science instrument observations at low altitude. Specifically, NEAR spent about 75 days in a 50 x 50 km polar orbit, about 10 days in a 35 x 35 km polar orbit, and about 57 days in a 35 x 35 km equatorial (retrograde) orbit. The direct orbits at these altitudes were avoided since they were found generally to be unstable. The elongated shape of Eros, with maximum radius of about 18 km, resulted in frequent passes at altitudes less than 17 km. There were also several transition orbits up to 200 km by 200 km where global observations were obtained.

The weak, non-spherical gravity field around Eros, combined with solar pressure accelerations, resulted in the low altitude NEAR orbits being highly perturbed, non-Keplerian, and difficult to predict. To estimate these orbits, the gravity field and its orientation in space also had to be estimated, and when using only radio metric data, made these estimates slow to converge. This required the use of optical landmark tracking, which used pictures of craters on Eros as landmark information, in addition to the more traditional radio metric tracking from NASA's Deep Space Network. The number of pictures processed and other statistics on the landmark tracking experience for the NEAR approach and orbit phase are shown in Table 1. To improve the spacecraft pointing knowledge for landmark image processing, occasionally the spacecraft would turn to point the imager at reference stars. The number of these sequences performed during the year long orbit phase are also shown in Table 1. The operational use of optical landmark tracking for a deep space mission was another navigation first for the NEAR mission.

Table 1. Operational summary of optical landmark tracking for NEAR over the entire approach and orbit phase.

Total number of pictures taken starting 12/17/1999	181,393	
Number of pictures downloaded to JPL for analysis	33,968	(18.73 %)
Number of useful pictures (at least 1 landmark)	17,601	
Number of accepted pictures (some had bad attitude)	17,352	
Number of on-orbit star calibration sequences	314	
Number of star calibration pictures	1,424	
Number of valid landmarks in database	1,590	
Number of landmark observations	134,267	
Number of misidentified landmark observations	1,314	(0.98 %)
Number of landmark observations in pictures with bad attitude	1,616	(1.20 %)
Number of useful landmark observations	131,337	(97.82 %)
Average number of useful observations per landmark	82.6	
Average number of useful observations per picture	7.6	

The NEAR mission posed several new and difficult challenges for spacecraft navigation. Many of these resulted from the fact that NEAR was the first mission to send a spacecraft to rendezvous with, orbit about, and finally land on an asteroid, the asteroid 433 Eros. The navigation team responded by developing new tracking data types and new processing methods specifically for NEAR navigation. Many of these methods should prove useful for navigation of future missions to asteroids and comets.

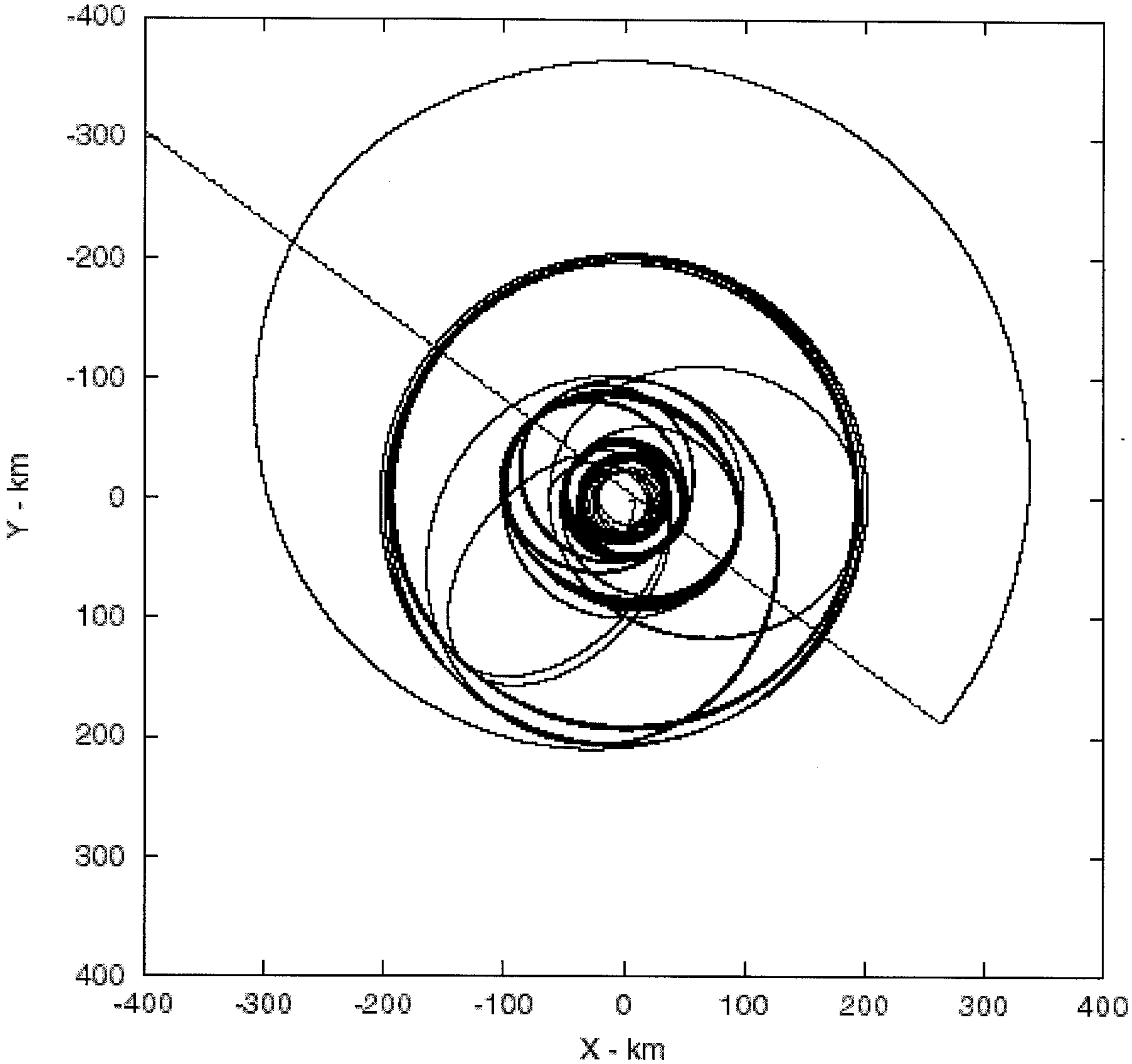

Figure 1. Complete approach (diagonal line) and orbit phase of NEAR covering February 14, 2000 to February 12, 2001 projected into the plane normal to the Sun-Eros line (the Sun plane-of-sky). The origin is at the center of mass of the asteroid 433 Eros. The end of mission descent to landing is shown as the crooked line near the origin.